- All matter is composed of atoms.
- Physical and chemical processes move atoms through ecosystems.
- Atoms cannot be created or destroyed.
- Atoms follow specific pathways through ecosystems.
- Human populations affect element cycles.

# THE Cycling of Elements THROUGH ECOSYSTEMS

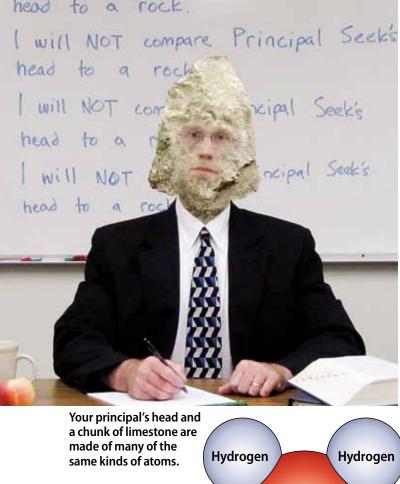
For a billion years, the atom bided time locked in a limestone shelf deep underground. Time means nothing to an atom that has existed forever and will always exist. Continents surfed slowly above, their grinding and colliding liquifying the limestone and moving the atom closer and closer to freedom. A volcano finally released the atom from its imprisonment. With a belch of superheated gas, the atom was discharged and airborne, as carefree as the wind upon which it now rode. The atom spent a decade in the atmosphere, sailing above supercontinents and immense oceans. One still morning, it drifted too close to the pore of a tree fern, and in the blink of an eye the atom was sucked into the helter-skelter world of living things.

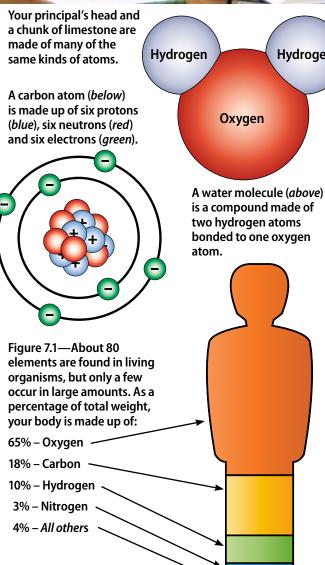
The atom helped build a leaf, which was promptly nipped off by a grazing brachiosaurus, which fell prey to the slashing jaws of an allosaurus, all in a single year. From its berth in the allosaur's bones, the atom did its part to keep the beast lumbering across the swampy land, but every living thing eventually dies, and the allosaur, despite its ferocity, was no exception.

Millennia passed, then epochs. The atom embarked on countless journeys in the bodies of creatures great and small—the hamstring of a Neandertal one year, the tooth of a saber-toothed cat the next. For a brief spell it returned to the atmosphere, but was quickly pulled earthbound to form an acorn, which fed a deer mouse, which fed a hawk. When the hawk died the following summer, the atom turned up in a blade of prairie grass, which fed a deer mouse, with neither atom nor hawk realizing the irony.

In time, the atom helped build a kernel of corn, which fed a beef cow, which became a cheeseburger that was eaten by an ecology student last night for supper. Presently, the atom is helping provide energy to the student, enabling her to think about what she is reading in class. The student, either from boredom or enlightenment, sighs. And, with that single breath, the atom is exhaled, free to sail the atmosphere yet again.

In the last chapter, we learned how energy from the sun makes a one-way trip through an ecosystem. Atoms, on the other hand, get recycled through ecosystems over and over again in a process ecologists call **element cycling**. In this chapter, we will learn about several atoms that are particularly important to life and explore how these atoms are recycled through ecosystems.





# All matter is composed of atoms.

How is your principal's head like a rock? Just like a rock, your principal's head is composed of atoms. In fact, if the rock were a chunk of limestone, your principal's head and the rock would be composed of many of the same kinds of atoms, such as carbon, oxygen and calcium. Two key differences exist, however, between a chunk of limestone and your principal's head. For one, your principal's head is composed of living cells, while limestone is composed of nonliving minerals. For another, the majority of atoms in limestone are arranged to form a single compound called calcium carbonate. The atoms in your principal's head, however, are arranged to form many different kinds of molecules, each playing an important role in keeping your principal alive and kicking. The point of this is that all matter—whether living or nonliving—is composed of atoms.

Atoms are classified as **chemical elements** based on the number of protons found in the atom's nucleus. For example, an atom of the element carbon has six protons in its nucleus. Elements can combine to form molecules and compounds. A **molecule** is formed when two or more atoms combine. The oxygen we breathe exists as a molecule of two oxygen atoms joined together by a chemical bond  $(O_2)$ . A **compound** is a molecule that contains at least two *different* elements. Water is a compound made of two hydrogen atoms bonded to one oxygen atom  $(H_2O)$ . All compounds are molecules, but not all molecules are compounds.

About 80 different elements are found in the cells and tissues of living organisms. Some elements are vital to life, but occur in small quantities in most organisms. Without iron, which is found in hemoglobin in red blood cells, your blood could not transport oxygen throughout your body. Iron, however, makes up only 0.006 percent of your body weight. Like iron, the majority of elements occur in tiny amounts in most organisms.

A few elements occur in large amounts in living organisms. About 65 percent of your weight comes from the oxygen atoms in your body. Carbon makes up about 18 percent of your weight, and hydrogen and nitrogen make up 10

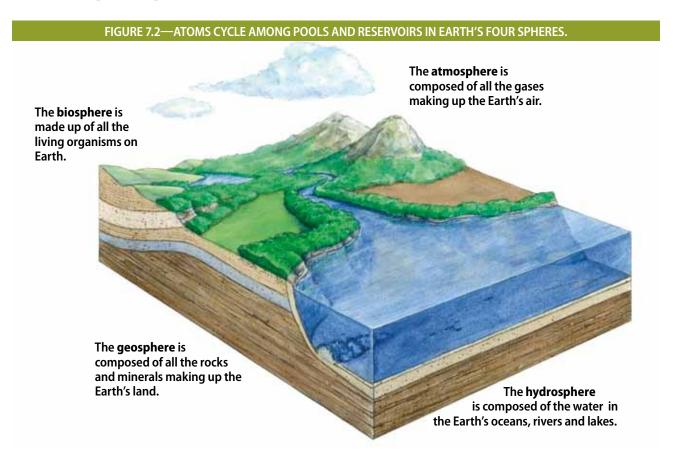
and 3 percent respectively (*Figure 7.1*). In fact, most of the mass of nearly any organism is made up of just five elements: oxygen, carbon, hydrogen, nitrogen and phosphorus. When combined in various ways, these elements form every carbohydrate, lipid, protein or nucleic acid. Carbohydrates, lipids, proteins and nucleic acids, which biologists call **biomolecules**, are the basic building blocks of cells, which, in turn, compose tissues, organs and organisms. Because of the relative importance of oxygen, carbon, hydrogen, nitrogen and phosphorus to living things, ecologists often study the availability and movement of these elements in ecosystems.

# Physical and chemical processes move atoms through ecosystems.

Organisms acquire the atoms they need from the ecosystem in which they live. Some organisms, such as humans and most other animals, obtain atoms by eating other organisms, drinking water and breathing air. Other organisms, such as plants and fungi, get atoms by absorbing them from their surroundings.

Organisms find atoms in various places within an ecosystem. Places where atoms collect for a short length of time—a few hours to a few years—are called **pools**. Places where atoms reside for longer periods of time—decades to millions of years—are called **reservoirs**. Ecologists generally lump all the pools and reservoirs where atoms can end up into four general "spheres" (*Figure 7.2*). The **biosphere** is made up of all the living organisms on Earth. The **geosphere** is composed of all the rocks and minerals making up the Earth's land. The **hydrosphere** is composed of the water in the Earth's oceans, rivers and lakes. The **atmosphere** is composed of all the gases making up the Earth's air.

Physical and chemical processes move atoms from one sphere to another. When water evaporates, hydrogen and oxygen atoms move from the hydrosphere to the atmosphere. This is a physical process. During photosynthesis and other biological processes, hydrogen and oxygen atoms in water are chemically rearranged to form various molecules that make up the tissues of plants and other organisms. Here, chemical processes move hydrogen and oxygen from the hydrosphere, geosphere and atmosphere into living things, which make up the biosphere.





The atoms that were here when Earth first formed are the same atoms organisms use today. An atom in the eyelash of a mastodon that lived thousands of years ago might be the same atom helping to form your fingernail today.

# Atoms cannot be created or destroyed.

Gravity keeps Earth's matter—even gases like oxygen and carbon dioxide—from floating off into space. This is good, because atoms, like every other part of the universe, are subject to certain physical laws. One of these, the **law of conservation of matter**, states that matter cannot be created or destroyed. This means that organisms cannot create new atoms whenever they need them. It also means that the atoms that were here when the Earth first formed are the same atoms organisms use today. Atoms are simply recycled and reused over and over again. In this way, a carbon atom in your toenail might have formed the eyelash of a mastodon or the tooth of a *Tyrannosaurus rex*.

Chemical processes can combine and rearrange atoms from one molecule into another. In each chemical reaction, however, the products of the reaction always balance the reactants. Look closely at the chemical equation for photosynthesis:

$$6CO_2 + 6H_2O (+ sunlight) \rightarrow C_6H_{12}O_6 + 6O_2$$

On the left side of the equation there are six carbon atoms, 18 oxygen atoms and 12 hydrogen atoms. On the right side there are the same amounts of each atom. Even though carbon dioxide and water get transformed into sugar and oxygen, the amounts of each kind of atom remain unchanged. In the next section, we'll explore how several atoms important to life are recycled, reused and rearranged as they move through ecosystems.

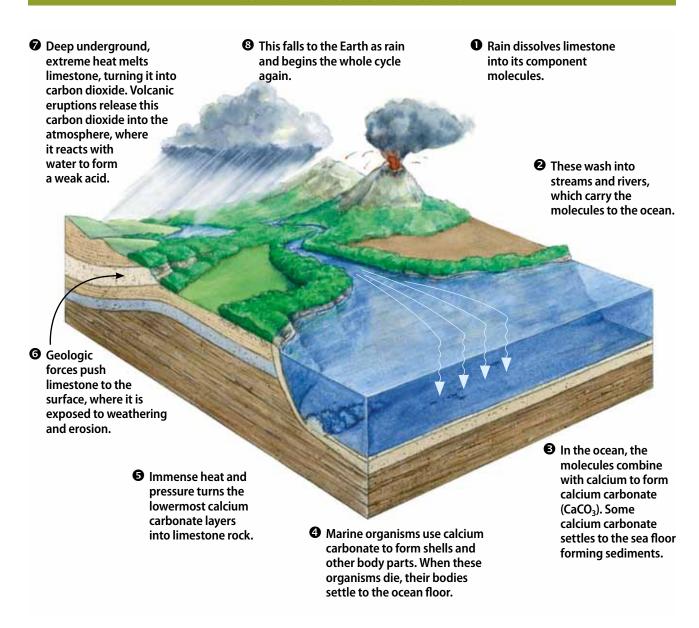
# Atoms follow specific pathways through ecosystems. THE CARBON CYCLE

Carbon, the fourth most abundant element in the universe, is the frame upon which every molecule (except water) used by living things is built. The vast majority—about 99 percent—of Earth's carbon is locked in the geosphere, mostly in sedimentary rocks, such as limestone, but also—though to a much smaller extent—in deposits of coal, oil and natural gas. Oceans and lakes contain the next largest pool of carbon, in the form of carbon dioxide (CO<sub>2</sub>) dissolved in water. Living organisms and the remains of dead organisms in the soil make up the third largest pool of carbon. Compared to the other pools and reservoirs, a relatively tiny amount of carbon exists in the atmosphere as carbon dioxide, and, to a lesser degree, methane (CH<sub>4</sub>).

Carbon moves among its various pools and reservoirs in two basic cycles—the **geological carbon cycle** and the **biological carbon cycle**. It takes millions of years for carbon to make the round trip through the geological cycle. The biological cycle takes a few hours to a few thousand years.

In the geological cycle, carbon moves among the geosphere, atmosphere and hydrosphere. Rain, which is a weak acid, can dissolve exposed limestone into its component molecules. These wash into streams and rivers, which carry the molecules to the ocean. In the ocean, the molecules combine with calcium to form calcium carbonate (CaCO<sub>3</sub>). Some calcium carbonate settles to the sea floor forming sediments. Other calcium carbonate molecules are used by marine organisms, such as mollusks and corals, to form shells and other body parts. When these organisms die, their bodies settle to the sea floor as well. As more and more calcium carbonate sediments are deposited, immense pressure turns the lowermost layers into limestone rock. When Earth's geologic plates shift, some of this limestone is pushed upward, where it becomes exposed to weathering and erosion. Other limestone is pushed deeper underground where extreme heat melts the limestone, turning it into carbon dioxide. Volcanic eruptions, thermal vents and geysers release this carbon dioxide into the atmosphere, where it reacts with water to form a weak acid. This falls to the Earth as rain and begins the whole cycle again.

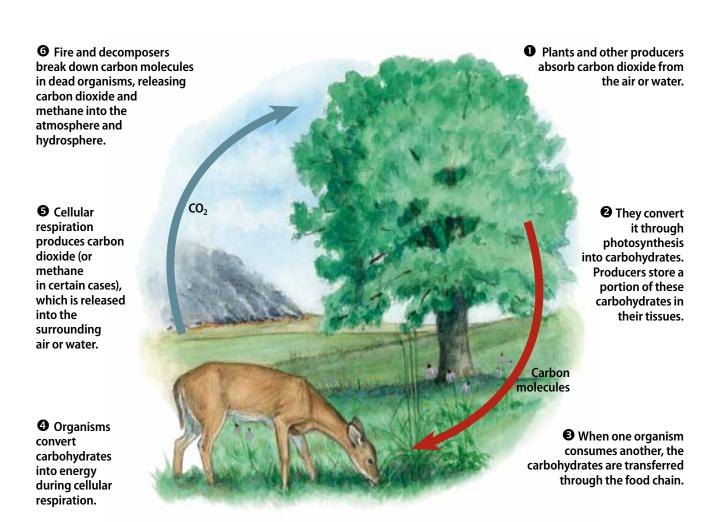
#### FIGURE 7.3—THE GEOLOGICAL CARBON CYCLE



The biological carbon cycle is closely tied to the flow of energy through ecosystems (*Figure 7.4*). Plants and other producers absorb carbon dioxide from the air or water, and convert it through photosynthesis into carbohydrates. Producers store a portion of these carbohydrates in their tissues. When one organism consumes another, the carbohydrates are transferred through food chains. Most carbon leaves the biosphere through cellular respiration, in which organisms use carbohydrates (and other molecules derived from them) for energy. The chemical reactions that take place during respiration produce carbon dioxide (or methane in certain cases), which is released into the surrounding air or water. Carbon can leave the biosphere in other ways. Fires consume organisms, releasing carbon compounds into the atmosphere. Bacteria, fungi and other decomposers break down carbon molecules in dead organisms, releasing carbon dioxide and methane into the atmosphere and hydrosphere.

When photosynthesis exceeds cellular respiration and decomposition, organic matter builds up in the geosphere. This happened about 300 million years ago, during the Carboniferous period, when billions of tons of organic matter was deposited and covered by sediments. Over millions of years, these deposits formed fossil fuels, such as coal, oil and natural gas. Burning fossil fuels releases the carbon once contained in prehistoric organisms back into the atmosphere.

#### FIGURE 7.4—THE BIOLOGICAL CARBON CYCLE



#### THE PHOSPHORUS CYCLE

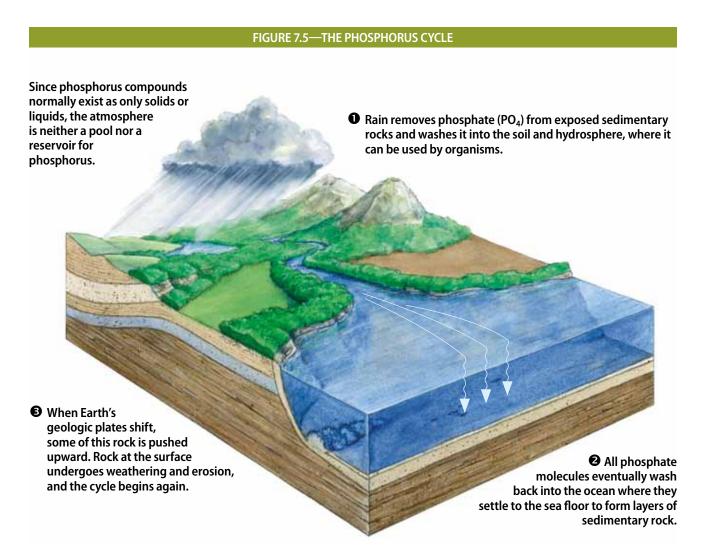
Although phosphorus makes up less than 1 percent of most organisms, life could not exist without it. Phosphorus helps form DNA, RNA and the energy molecule ATP. It is a structural component of cell membranes, bones and teeth. Compared to other element cycles, the phosphorus cycle isn't complicated, but it is slow (*Figure 7.5*). It normally takes millions of years for phosphorus to cycle among the geosphere, biosphere and hydrosphere.

At Earth's normal temperatures and pressures, phosphorus compounds exist only as solids and liquids. Therefore, the atmosphere is neither a pool nor a reservoir for phosphorus. The largest reservoir of phosphorus occurs in sedimentary rocks in the Earth's crust. Rain removes phosphorus in the form of phosphate  $(PO_4)$  from these rocks and washes it into the soil and hydrosphere, where it can be used by organisms.

Phosphorus moves into food chains when plants absorb phosphate through their roots. Other organisms obtain phosphorus by eating plants or other organisms. Decomposers return phosphates to the soil by breaking down dead organisms or the wastes that organisms produce.

In some soils, plants cannot absorb phosphate by themselves and must team up with fungi to get the phosphorus they need. In this mutualistic relationship, called **mycorrhizae**, plants provide fungi with carbohydrates. In return, fungi gather phosphates and other nutrients with their vast network of **mycelia**, tiny, thread-like organs that gather water and nutrients.

All phosphate molecules eventually wash back into the ocean where they settle to the sea floor and form layers of sedimentary rock. When Earth's geologic plates shift, some of this rock is pushed upward. Rock at the surface undergoes weathering and erosion, and the cycle begins again.





Nitrogen gas makes up 78 percent of the air we breathe, but few organisms can use nitrogen in this form.

#### THE NITROGEN CYCLE

Nitrogen is an essential part of DNA, RNA and amino acids. It helps form chlorophyll, the green pigment involved in photosynthesis. The major reservoir of Earth's nitrogen is the atmosphere. In fact, 78 percent of the air we breathe is composed of nitrogen gas  $(N_2)$ . Few organisms can use nitrogen in this form, however. Instead, it must undergo a process called **nitrogen fixation**, which changes nitrogen gas into ammonia (NH<sub>3</sub>) (Figure 7.6). Nitrogen can be fixed in three different ways:

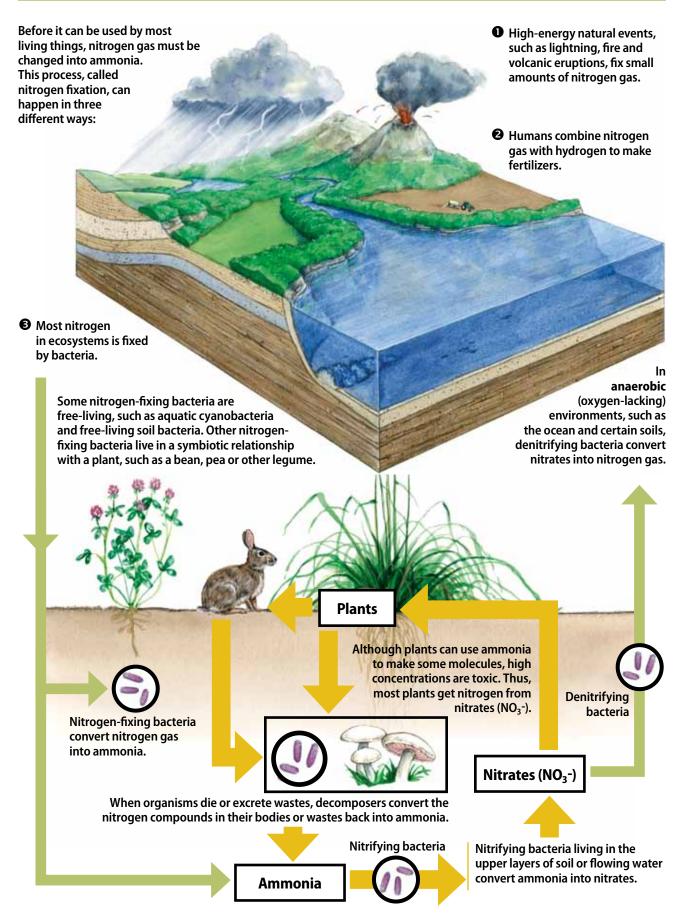
- High-energy natural events, such as lightning, fire and volcanic eruptions, fix small amounts of nitrogen gas.
- Humans combine nitrogen gas with hydrogen (usually a byproduct from fossil fuels) to make nitrogenbased fertilizers.
- Most nitrogen in ecosystems is fixed by bacteria. Some nitrogen-fixing bacteria are free-living, such as aquatic cyanobacteria and free-living soil bacteria. Other nitrogen-fixing bacteria live in a symbiotic relationship with a plant, such as a bean, pea or other legume. In this relationship, the plant provides bacteria with carbohydrates to fuel nitrogen fixation, and the bacteria provide the plant with a useable form of nitrogen.

Plants can use ammonia to make proteins and other nitrogen-based molecules. High concentrations of ammonia, however, are toxic. Because of this, most plants get nitrogen from nitrates (NO<sub>3</sub>-). A different kind of bacteria, nitrifying bacteria, convert ammonia into nitrates through a process called **nitrification**. Nitrification requires oxygen, so it only happens in oxygen-rich environments, such as upper layers of soil or flowing water.

Once nitrogen is incorporated into plant tissues, it can travel through food chains to other organisms. When organisms die or excrete wastes, decomposers convert the nitrogen compounds in their bodies or wastes back into ammonia.

Ammonia sticks to soil particles and stays put. In contrast, nitrates dissolve in water and can wash out of the soil into the hydrosphere, where they eventually end up in the ocean. Here, in anaerobic (oxygen-lacking) environments, denitrifying bacteria convert nitrates into nitrogen gas. This process, called **denitrification**, also occurs in anaerobic soils. Denitrification removes nitrogen from the biosphere, geosphere and hydrosphere and returns it to the atmosphere.

#### FIGURE 7.6—PHYSICAL AND BIOLOGICAL COMPONENTS OF THE NITROGEN CYCLE

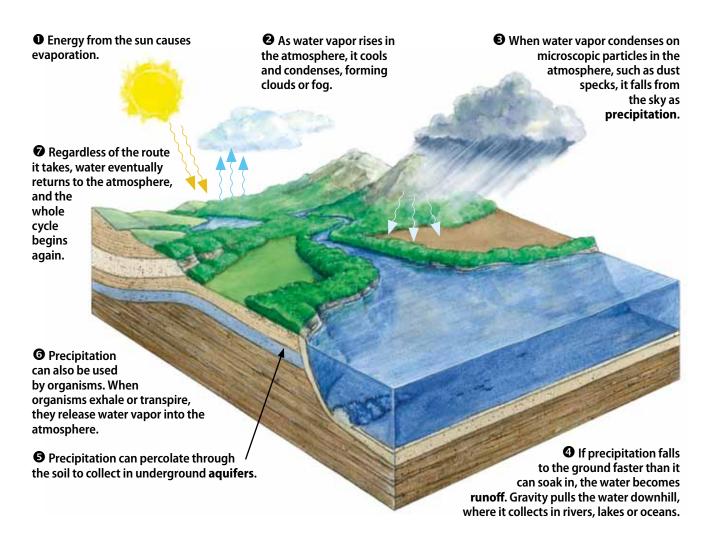


#### THE WATER CYCLE

Although water is a molecule—not an element—it is one of the most important ingredients of life. Water-based fluids, such as blood and cytoplasm, play a vital role in transporting substances throughout the bodies of organisms. Water keeps the internal temperature of many organisms from changing too rapidly when the ambient temperature changes. For many organisms, including earthworms, jellyfish and plants, water is a supporting structure. (This is why plants wilt when they lose too much water.) Water plays a role in reproduction. For a sperm to fertilize an egg, for example, it must travel through water-based fluids. Water is a reactant or product in many chemical reactions that occur inside organisms, including photosynthesis and cellular respiration. In addition, water is a key habitat component for a vast array of organisms, from bacteria to bluegills.

The Earth contains enough water to fill about 700,000,000,000,000,000,000 two-liter soda bottles. More than 97 percent of this water resides in the oceans, rivers and lakes of the hydrosphere. About 2.9 percent is found in the geosphere, either frozen in polar ice caps and glaciers, contained in soil, or pooled in underground aquifers. Water vapor in the atmosphere accounts for 0.001 percent of Earth's water. Living organisms—which make up the biosphere—contain a scant 0.00008 percent of Earth's water. The movement of water among these different spheres is called the **water cycle** (*Figure 7.7*).

#### FIGURE 7.7—THE WATER CYCLE



Because water is composed of oxygen and hydrogen atoms, the water cycle is an important way that oxygen and hydrogen move through ecosystems and become available to living organisms. Some water moves between the biosphere and other spheres through the chemical reactions that occur inside organisms. Most of the water cycle, however, is driven by two physical factors—solar energy and gravity.

The sun warms water on the Earth's surface and changes it into water vapor. This change of state—from liquid to gas—is called **evaporation**. Evaporation moves water from the geosphere and hydrosphere to the atmosphere. Living organisms can also move water to the atmosphere. Every time you exhale, you breathe out water vapor. Plants release water vapor into the atmosphere through their stomata, which are microscopic pores in the plant's leaves and stems. This process, called **transpiration**, helps plants release excess water resulting from photosynthesis and cellular respiration. Transpiration also helps cool the plant when temperatures are high.

As water vapor rises in the atmosphere, it cools and changes back into liquid, forming clouds or fog. This change of state—from gas to liquid—is called **condensation**. Water vapor also condenses on ground-level surfaces as dew. When water vapor condenses on microscopic particles in the atmosphere, such as dust specks, it can fall from the sky as **precipitation**. Condensation and precipitation move water from the atmosphere to the hydrosphere and geosphere.



Precipitation falling on land can take several routes through an ecosystem. It can be taken up by organisms, in which case it is eventually exhaled or transpired as water vapor. It can percolate through soil and other porous surfaces, where it can be absorbed by the roots of plants or collect in **aquifers**, underground pools in the pores and crevices of bedrock. If precipitation falls to the ground faster than it can soak in, the water becomes **runoff**. Gravity pulls the water downhill, where it eventually evaporates or collects in streams, rivers, lakes or oceans. Regardless of the route it takes, water eventually returns to the atmosphere, and the whole cycle begins again.

### Human populations affect element cycles.

Because of gravity and the conservation of matter, the Earth is a closed system. When atoms move out of one pool or reservoir, they must reside in another. Historically, natural events such as volcanic eruptions, meteorite strikes or changes in the Earth's orbit have altered how atoms are distributed. Within the last 200 years—the blink of an eye in geologic time—human activity has become another significant force changing the distribution of atoms in Earth's various pools and reservoirs. This has important consequences for humans and other organisms.

Human activity has increased the amount of nitrogen and phosphorus in the biosphere. To make fertilizers, humans mine phosphorus from the geosphere and fix nitrogen from the atmosphere. Fertilizers are applied to lawns, golf courses and crop fields to increase plant growth. Too much fertilizer, however, can lead to **eutrophication**, which devastates biological communities. Eutrophication occurs when large amounts of fertilizers run off the land into watersheds. The build-up of nitrogen and phosphorus in rivers, lakes and oceans, stimulates the growth of enormous amounts of algae, aquatic plants and other producers.



When these organisms die, decomposition removes oxygen from the water. Without adequate oxygen, other aquatic organisms die, causing the aquatic ecosystem to collapse. Human sewage and industrial wastes also cause eutrophication.

Through deforestation and the burning of fossil fuels, humans move enormous quantities of carbon into the atmosphere. Carbon-based gases, such as carbon dioxide and methane, are known as **greenhouse gases** because they allow sunlight to pass through but trap heat—just like the panels of a greenhouse. Without greenhouse gases, the Earth's average surface temperature would be minus 17 degrees Celsius—too cold for life to flourish. As greenhouse gases build up in the atmosphere, however, temperatures are increasing at rates that alarm some scientists.

According to climate scientists around the world, in the last 100 years, Earth's average temperature has increased by 0.7 to 0.8 degrees Celsius. If greenhouse gases continue to increase, models predict Earth's temperature could increase by 1.8 to 4.0 degrees Celsius by the end of this century. These models are imprecise, however, and scientists are unsure how fast climate change will occur and how warming will affect earth's ecosystems.

Humans affect the distribution of water through consumption and pollution. Water is used to irrigate crops, water livestock, produce goods, and for drinking, cooking and washing. From 1900 to now, the human population has doubled, but we use six times the amount of water! In fact, humans use so much water in some parts of the world that we've drained rivers dry, and we've pumped so much water out of underground aquifers that the ground has sunk in certain areas. Sewage and industrial wastes pollute water, making it unusable to humans and other organisms. All of this has led to water shortages throughout the world, which affect the survival not only of humans, but of all organisms. Unless solutions are quickly implemented, global water shortages and climate change could reshape Earth's ecosystems, profoundly affecting biological communities and the economies, politics and stability of human societies.  $\triangle$ 



# **Keeping Harmful Elements Out of Ecosystems**

During a typical dove season at Columbia Bottom Conservation Area, hunters shoot about 32,000 shotgun shells, each containing an average of one ounce of shot. This works out to 2,000 pounds—a ton—of shot deposited on the ground each year. Lead shot is banned at Columbia Bottom. Instead, hunters must shoot shells filled with steel or other types of nontoxic shot. Why?

When foraging for food, doves, waterfowl and many other birds swallow pieces of grit and gravel. The pebbles are stored in a muscular stomach called the gizzard. Birds don't have teeth and can't chew and grind up food. That's where the gizzard comes in. When the gizzard contracts, the pebbles inside pulverize hard foods like seeds, nuts and invertebrates, making them easier to digest.

To a bird, a lead shotgun pellet looks like any other bit of rock it might eat to keep its gizzard stocked. When the lead reaches the gizzard it is worn down, dissolved and absorbed into the body. Lead, however, is toxic in even small concentrations and causes irreparable bone, nerve and muscle damage. Studies have shown that up to 6 percent of the doves feeding at Columbia Bottom could die from lead poisoning each year if nontoxic shot were not required for hunting.

Lead poisoning is a terrible way to die. When a bird ingests too much lead, it gets weak, loses weight, and eventually becomes paralyzed. Many birds starve to death. Others become so weak they make easy pickings for predators. Some birds, particularly waterfowl, drown when they cannot hold their heads above water. Studies reveal that 31 species of birds can fall victim to lead poisoning.

Lead can work its way up the food chain and kill other animals, too. Lead poisoning has been found in raccoons, mink and birds of prey. Between 1994 and 2003, the Wisconsin Department of Natural Resources examined 559 dead bald eagles. The researchers found that 68 of the eagles—12 percent—had died from lead poisoning.

In 1990, the Conservation Department banned the use of lead shot for waterfowl hunting in Missouri. A year later, lead shot for waterfowl hunting was banned nationwide. In 2007, Missouri expanded its lead shot ban to include all types of shotgun hunting on 21 of Missouri's conservation areas. These areas have extensive wetlands and large concentrations of doves, waterfowl and shorebirds.

The U.S. Fish and Wildlife Service estimates that prior to 1991, 1.6 to 2.4 million waterfowl died *each year* from lead shot poisoning. Now, thanks to the use of nontoxic shot, those numbers are much lower.



